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EXPLORATION OF THE ATMOSPHERE OF VENUS BY A SIMPLE CAPSULE

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SUMMARY

The exploration of the planet Venus by probes which penetrate the atmosphere will allow direct measurements of very important physical parameters. Early probes must be restricted to a few simple instruments but, carefully chosen, they will yield a truly remarkable increase of knowledge. These results will then pave the way for more sophisticated instruments, to be considered as second and third generation. The main target of the early experiments should be the structure and composition of the atmosphere. Accordingly, pressure, temperature, and density will be measured as well as the nitrogen, carbon dioxide, argon, water vapor, and cloud content. Simple methods to determine these parameters are discussed.

CONTENTS

List of Symbols

A	cross-sectional area
C_D	aerodynamic drag coefficient
C_p	specified heat at constant pressure
C_V	specified heat at constant volume
c	velocity of sound
g	gravitational force on Venus
H	scale height
h	height
M	molecular weight
m	mass
p	pressure
R	gas constant
T	temperature
t	time
u	descent velocity of probe
z	acoustical impedance
Γ_{ad}	adiabatic lapse rate
Γ_{obs}	observed lapse rate
γ	specific heat ratio
ρ	density

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INTRODUCTION

Earthbound observations of reflected, refracted, and emitted radiation in several regions of the electromagnetic spectrum have been the principal source of information about the planet Venus. Only recently, after the successful adventure of Mariner II (1962 $\alpha\rho 1$), have other data, such as the absence of a strong magnetic field, become available.

Large and complicated instruments serve the earthbound astronomer and he can, within reason, repeat his experiment or observation as often as he desires. However, surface observations suffer from the small solid angle which the planet subtends and from the interference of the Earth's atmosphere. In spite of these limitations remarkable results have been achieved. These results have been summarized by Moore, Urey, and Kuiper (References 1-3), and more recently by Kellogg and Sagan, de Vaucouleurs, Kuiper and Middlehurst, Öpik (References 4-7), and others.

The most important sources of data about Venus can be classified according to the technique and the part of the electromagnetic spectrum used, under one or more of the following headings:

1. General astronomical data - mass, size, orbital parameters, etc.
2. Planetary photometry - albedo at various wavelengths, cloud markings, etc.
3. Polarization studies (References 8-10).
4. Near infrared spectroscopy (References 11-17).
5. Far infrared radiometry and spectroscopy (References 18-24).
6. Occultation method (Reference 25).
7. Radar and microwave radiometry (References 26-31).
8. Mariner II measurements.

MODELS OF VENUS

On the bases of theoretical considerations and the experimental evidence just listed (or some part of it), attempts have been made to generate a consistent picture of the atmosphere and surface of Venus. Each attempt usually culminates in a "model" which matches at least a few and hopefully all of the experimental data. These models allow extrapolation to facts which are inaccessible by direct measurements from Earth. It is characteristic of the state of knowledge about Venus that the number of atmospheric models almost exceeds the number of experimental facts. Only a few recent models, those discussed by Kellogg and Sagan (Reference 4), will be mentioned here.

The Greenhouse Model

The radiometric temperature (≈600°K) in the microwave region is believed to be the temperature of the surface of Venus (Reference 32). An atmosphere fairly transparent in the region of solar radiation but opaque in the region of thermal radiation provides the energy-tapping or greenhouse effect. A fairly high amount of water vapor should exist below the clouds, but this has not been confirmed by recent microwave data. The surface pressure would be much higher than on Earth, presumably 2 to 5 atmospheres; a more recent estimate yields even 50 atm. (Reference 33).

The Aeolospheric Model

Öpik (Reference 34) also accepts the high temperature in the microwave region as coming from the surface. However, here the high temperature is maintained by friction among grinding particles in the atmosphere. A very dusty atmosphere effectively isolates the surface from solar radiation as well as from thermal cooling. This model seems to be the most reasonable one, but its agreement with certain theories, such as the general circulation theory, has yet to be substantiated.

The Ionospheric Model

In contrast with the previously mentioned models, the ionospheric model explains the high microwave temperature by emission from a very dense ionosphere. This model, almost discarded a year ago, temporarily achieved new support from measurements indicating the absence of a magnetic field (Mariner II) and from the discovery of an apparent correlation between Venus radar data and solar flux in the 20 cm region (Reference 35). However, tentative information on limb darkening, determined by the microwave radiometer on Mariner II, seems to rule out this model.

Other Models

In addition to the above-mentioned models much has been published that at times contains implicit statements equivalent to particular models. Only a few of the writers need be mentioned: de Vaucouleurs, Chamberlain and Kuiper, Sinton and Strong, Barrett, Kaplan, and Mintz (References 5, 15, 24, 36, 37, and 38).

In spite of these efforts the atmosphere of Venus remains a puzzle. Basic parameters such as surface pressure are uncertain to approximately 2 orders of magnitude—the value for pressure varies from 0.3 atm. for the ionospheric model to perhaps 50 atm. for the greenhouse model (Reference 33); the relative abundance of CO_2 is quoted as high as 80 percent (Reference 7) and as low as 4 percent (Reference 16) and de Vaucouleurs quotes seven different suggestions for the composition of the visible clouds, some more likely than others (Reference 5). Even the orientation of the axis of rotation and the rotation rate are uncertain. Estimates of the latter range from 10 to 225 days and there is evidence for both direct and retrograde rotation.

In summary, the experimental data about Venus are not only limited but inconsistent as well. It seems that observations from the surface of the Earth will yield further results. For example, better estimates of the CO_2 concentration are expected from near infrared spectroscopy and much can be learned with more powerful radar instruments. More promising still are the high-altitude balloon-borne spectroscopic experiments planned by Schwarzschild (Princeton University), which will elevate fairly elaborate equipment above much of the earth's atmosphere. But, in general, earthbound methods have been well explored.

Another means of obtaining information is from fly-by platforms. Although these will completely overcome the limitations imposed by the Earth's atmosphere and will "magnify" the planet by passing rather close to it, they will do so at the expense of the information rate in the telemetering link. In addition, it is likely that only simple instruments will be flown within the next decade.

DIRECT EXPLORATION OF THE ATMOSPHERE OF VENUS

All the techniques discussed so far, earthbound and balloon-borne instruments and fly-by spacecraft, have one basic limitation in common — they have to infer many physical parameters from observations at a distance. Although in theory it is possible to derive pressure, temperature, and composition from spectroscopic measurements taken outside an atmosphere, without knowledge of the altitude distribution and the nature of the reflecting layers, these spectroscopic data are subject to misinterpretation. Certain crude assumptions can be made and may be justified as first attempts to solve the puzzle, but a final settlement of the physical and chemical states of the atmosphere and its circulation, as well as planetary surface properties, can be obtained much more easily and more accurately by *in situ* measurements performed by a probe which penetrates the atmosphere of Venus. The basic parameters (pressure, temperature, and composition) which describe an atmosphere could be measured directly with very simple and reliable instruments, and would not have to be extracted from difficult spectral observations.

By studying the parameters which should be determined with an entry probe and the engineering problems involved, it becomes apparent that possible *in situ* experiments and instruments may be divided into three classes: (I) elementary, (II) advanced, and (III) future, or those which are reasonable within 5, 10, and 20 years.

Class I

This group is considered the first generation of experiments capable of making measurements within the atmosphere of Venus. The total weight of all sensors, including their electronics, can be set at about 5 kg. The total payload includes communication components, batteries, and structure, and will weigh roughly 50 kg; an information rate of 1 bit per second will suffice. The primary goal of the experiments is a basic and general understanding of the atmosphere, and pressure, temperature, and density profiles are essential for this. As much as possible should be learned about the composition of the atmosphere, including the altitude distribution and the particle composition of the clouds. A small number of simple experiments should be more than sufficient to show which model atmosphere is correct, and in fact will allow a more definitive model to be established. It can be visualized that this kind of payload not only will be used for the first two or four attempts but also will supplement more complicated missions in the future. For early attempts the heat shield must be overdesigned; later, however, better data on the atmospheric composition will permit reduction of the heat shield weight and a corresponding increase in payload weight. Overall weight and size should stay fairly constant, but succeeding experiments could vary and be made more specific. Also, early versions of the class II experiments may even be flown on later class I vehicles.

Class II

Obviously, the detailed planning of this vehicle and its experiments will be strongly influenced by the results of the class I experiments. The main purposes of this investigation will be to refine the atmospheric profiles determined by class I probes and to obtain information about the surface. Thus, successful landing on the surface is required. The sensors can have a weight up to 25 kg, and the total weight of the capsule including transmitter and power supply (possibly nuclear) will be about 200 kg. Transmission rates of 16 bits per second and greater can be expected for direct transmissions.

Mass spectrometers will determine trace elements and refine estimates of the atmospheric constituents. The composition of clouds and the size distribution, polarization, and scattering properties of particles will also be determined. In addition, a radar altimeter will provide more accurate altitude determinations; it will allow a fast descent through most of the atmosphere and the deployment of a parachute just before impact. Such a mission will avoid excessive heating in the lower atmosphere during descent if the lower atmosphere should be as hot as 600 °K. Survival at the surface for as long as several hours is also feasible with insulating techniques and heat dissipation through phase conversion. The nature of the surface, wind speed, barometric fluctuations, radioactivity, precise measurements of surface gravity, and other data can then be determined.

Class III

This system is the most advanced exploration system visualized, short of manned exploration. It will utilize microscopes and television cameras. Chemical analysis of surface material, determinations of the rotation rate of Venus (by gyros), refinement of ionospheric and atmospheric data, and even subsurface exploration can be carried out. In addition, constant-level balloons drifting in the atmosphere of Venus with long-life batteries could help to determine wind speed and the circulation patterns. The specific design of the class III mission must rest so much on the results of the earlier missions that a further discussion of class III experiments becomes purely academic.

PHYSICAL PARAMETERS

Before considering specific instruments and techniques applicable to an early class I probe, a brief discussion of the physical parameters to be measured is in order. The conclusions which can be drawn from a set of measurements will be developed with the use of the information diagram shown in Figure 1.

It is appropriate to mention here that the purpose of this paper is to describe a set of experiments that would be suitable for early Venus entry capsules, and that it is not addressed to any particular mission or program. The descriptions merely represent preliminary models and, although presented in the indicative mood for ease of expression, should not be interpreted as representing a final selection of experiments for a specific Venus mission.

On the left side of Figure 1 are listed particular physical parameters to be measured, specifically the atmospheric pressure, temperature, velocity of sound, acoustical impedance of the gas, CO_2 and water vapor concentrations, and presence of clouds. For all these, the time of observation must also be accurately known. The individual sensors measure quantities which lead to the determination of secondary parameters as indicated by arrows and the symbols in the rectangular blocks. The following are pertinent equations:

$$\rho_1 = \frac{C_D A}{2g^3 m}\left(\frac{\Delta p}{\Delta t}\right)^2, \qquad M_1 = \frac{C_D ART}{2g^3 mp}\left(\frac{\Delta p}{\Delta t}\right)^2, \qquad h_1 = \int_t^{t_0}\left(\frac{2mg}{\rho C_D A}\right)^{1/2} dt,$$

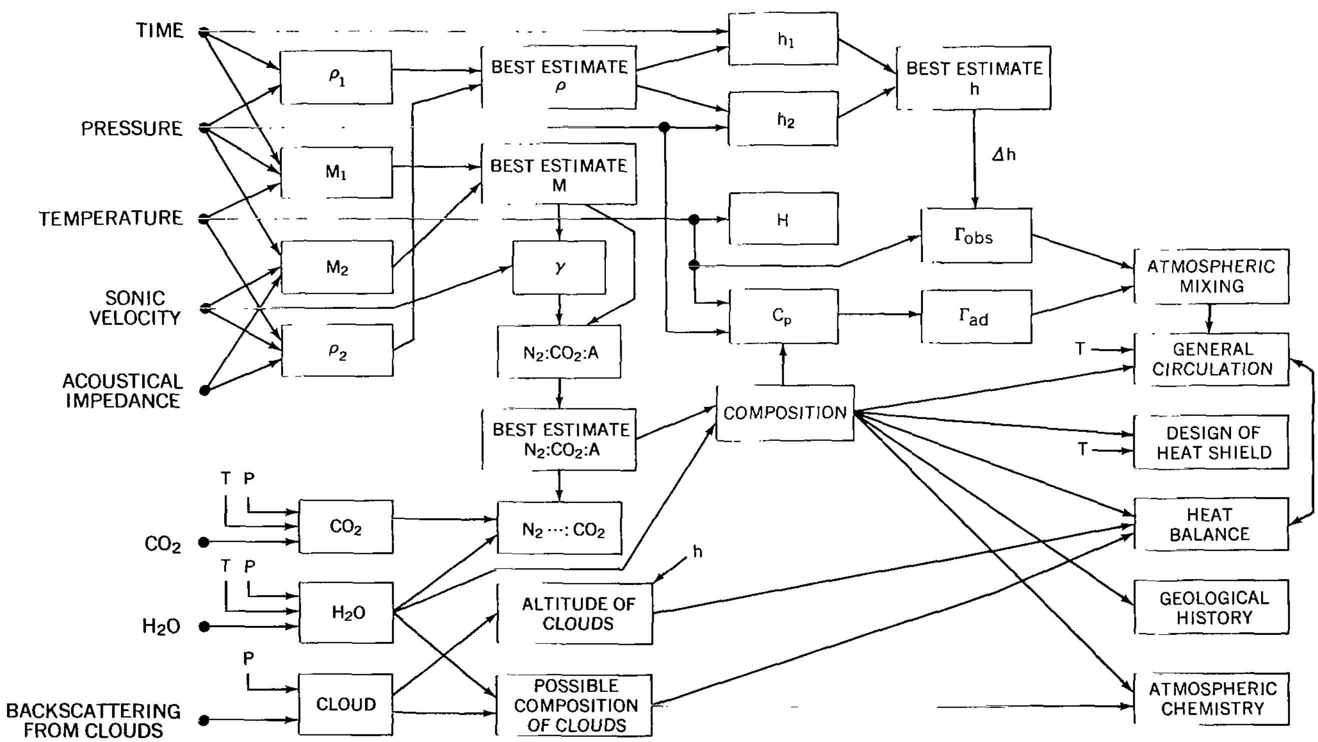

Figure 1—Some of the physical parameters of the planet Venus and its atmosphere that can be derived from a small number of sensors making *in situ* measurements.

$$\rho_2 = \frac{zT_3}{cT}, \qquad M_2 = \frac{zRT}{cp}, \qquad h_2 = \int_p^{p_0} \frac{dp}{\rho g},$$

$$\gamma = \frac{C_p}{C_v} \qquad \Gamma_{ad} = \frac{-g(h)}{C_p}, \qquad H = \frac{RT}{Mg}.$$

T_3 is the temperature of the tube used for the acoustic experiment. Certain parameters, such as the density, can also be determined independently by different methods. One of the methods for determining the density needs only an accurate pressure vs. time relation. The mass m of the descending body and its aerodynamic drag coefficient C_D must be known. Because of the uncertainties in the amount of ablation material lost during the entry phase, this technique clearly requires dropping the heat shield before the sequence of measurements begins. Another method, based on the acoustical properties of the atmosphere, yields a more accurate density estimate.

Whenever possible, attempts have been made to determine important parameters by more than one method, the second being an independent method if feasible. Altitude, density, and mean molecular weight are determined by totally or at least partially independent means. Fundamental parameters such as temperature and pressure must be recorded by duplicate instruments. The carbon dioxide concentration is determined directly by a specific sensor and also indirectly from the ratio of nitrogen to carbon dioxide to argon. This is significant; if the two CO_2 determinations agree, the hypothesis assumed in the acoustical determination of the N_2:CO_2:A ratio (that N_2, CO_2, and A are the major constituents of the Venus atmosphere) is proven.

The duplicate and independent determination of important parameters provides a number of advantages considered essential for scientific exploration:

1. Close agreement between the results of independent experiments gives confidence in the measurements.
2. Error analysis on two independent experiments can improve the accuracy to which a quantity can be determined.
3. Since the number of relations which exist between the measured parameters is greater than the number of parameters, the system is overdetermined and the loss of a sensor is not as catastrophic as it is in a system which is not overdetermined.

The information flow diagram further shows how information from the sensors contributes to an understanding of the general circulation in the atmosphere, the mixing in the layers below and above the clouds, and the heat budget and thermal structure in the atmosphere below the clouds. Atmospheric chemistry, photodissociation theory, and surface chemistry can be used to improve and extend knowledge about Venus. A knowledge of the existence of clouds at a certain pressure and temperature and a knowledge of the phase diagrams of possible chemical substances will rule out certain cloud hypotheses and may help to determine the composition of the clouds.

It should be pointed out that the flow diagram (Figure 1) is by no means complete. Many more conclusions can be drawn from these simple experiments. The flow diagram shows only what is derived from the sensors in the probe. Although existing knowledge also has to be fed into this pattern, it has been omitted from Figure 1 to avoid needless complication. The main purpose here is to show the great amount of information that can be derived from a rather small number of carefully chosen but basically simple experiments. As will be shown later, the instruments do not contain moving parts which require lubrication; so the calibration (if not a built-in property of the instrument) can be maintained during the long journey in space as well as during the rather severe entry phase. A detailed description of possible experiments follows.

PRESSURE

It is proposed to measure the ambient pressure during the descent phase, after the capsule has reached a descent speed below Mach 1. Individual potentiometer-type pressure gauges with ranges of 0.7, 7, and 70 atm. will be used in an arrangement which provides complete redundancy. The units will have an accuracy of ±2 percent even after a 140°C baking period of 24 hours or more.

Pressure data are used in the determination of the density, altitude, mean molecular weight, and composition of the atmosphere. One method of determining the density and mean molecular weight uses primarily the pressure data and therefore will be discussed under this heading. For other cases when the pressure is used in conjunction with other information the particular technique will be described in a separate section.

A capsule descending in a planetary atmosphere reaches terminal velocity very quickly, and gravitational and aerodynamic forces then balance each other:

$$mg = \frac{1}{2} C_D A \rho u^2 .$$

Because of the uncertainties in the loss of ablation material during the entry phase, it is clear that the heat shield must be dropped; otherwise, the descending mass m and the drag coefficient C_D will not be known accurately enough. From the hydrostatic relation

$$\frac{dp}{p} = -\frac{dh}{H}$$

and (neglecting any vertical wind component)

$$u = \frac{dh}{dt} ,$$

the density can be found:

$$\rho = \frac{C_D A}{2g^3 m} \left(\frac{dp}{dt}\right)^2 .$$

Since $\overline{M} = \rho RT/p$, the mean molecular weight is

$$\overline{M} = \frac{C_D ART}{2g^3 mp} \left(\frac{dp}{dt}\right)^2 .$$

From the mean molecular weight an estimate of the CO_2 content can be obtained; $\bar{M}$ = 28 for N_2 only and $\bar{M}$ = 44 for CO_2 only.

To indicate the advantages and the shortcomings of this method, an estimate of the expected accuracy will be made. The probable error in the determination of the CO_2 content of the Cytherean atmosphere is calculated under the following assumptions:

1. The atmosphere consists mainly of N_2 and CO_2.
2. The probable error in the temperature measurement is ±2 percent between 180° and 330°K.
3. The factor C_DA has been determined carefully in the Earth's atmosphere, and the value is correct for Venus to within ±2 percent.
4. The pressure is measured to ±2 percent full range but readings are taken at only half range, resulting in a probable error in p of ±4 percent.
5. The mass of the descending assembly (capsule plus parachute, without heat shield) is known to better than ±0.5 percent.
6. The gravitational constant of Venus is known to ±1 percent.
7. The differential dp/dt can be derived from a series of pressure and time readings; and smoothing techniques yield about the same accuracy as the pressure measurement: ±4 percent.

The probable error (root mean square) in the mean molecular mass $\bar{M}$ is then about ±7 percent, which corresponds to a probable error in the CO_2 content of ±15 percent for $\bar{M} \approx 35$. By making somewhat more optimistic assumptions (which may become severe for actual instruments), the probable error can be lowered to perhaps ±10 percent but this will be difficult to achieve.

Clearly, this technique is not the most accurate one; but it is readily available since pressure, temperature, and time will certainly be measured with an early probe. Although a ±10 percent accuracy in CO_2 concentration is not too impressive, the technique is capable of distinguishing between a low, medium, or high CO_2 content in the atmosphere of Venus.

TEMPERATURE

It is proposed to measure the ambient gas temperature during the descent phase, after the capsule has reached Mach 1. The temperature sensors will be platinum resistance elements with temperature ranges from 150° to 750°K and from 180° to 330°K. The first range is intended to give the overall temperature profile down to the surface. The second range is intended primarily to provide a higher accuracy in the vicinity of the visible cloud layers, since accurate temperature values will be very important in identifying the cloud composition.

The temperature reading will have a probable error of about ±2 percent, corresponding to ±12°K for the 150° to 750°K range and ±3°K for the smaller temperature range. The errors quoted include aerodynamic heating and calibration errors, and errors introduced in amplifying and quantizing the information in the capsule for transmission. The temperature data are used in the determination of many other physical parameters; for example, determination of the molecular weight, scale height, density lapse rate, and composition requires the value of the ambient gas temperature directly or in correction terms.

MOLECULAR MASS, DENSITY, AND SPECIFIC HEAT RATIO

The experiment for finding the values for the molecular mass, density, and specific heat ratio has been discussed previously for a Mars mission (Reference 39). The instrumentation will be identical for Venus except for minor changes, such as reduction of the microphone spacing to accomodate a wider dynamic range. $\overline{M}$, ρ, and the mean specific heat ratio $\overline{\gamma} = C_p/C_v$ will be determined by acoustical means. The velocity of sound in a gas c is a function of T, M, and $\overline{\gamma}$, and is given by $c^2 = \overline{\gamma}RT/\overline{M}$, where R is the gas constant. This well-known relation has been used in the past in various techniques to measure the temperature of the Earth's atmosphere, where $\overline{M}$ and $\overline{\gamma}$ were accurately known. It is proposed to reverse this method and bring a volume of the atmosphere of Venus into a thermostatically controlled tube where the temperature is known accurately and to determine $\overline{M}/\overline{\gamma}$ by measuring the velocity of sound through the medium in the tube. Simultaneously, the acoustical impedance of the gas in the tube will be measured, and division of the acoustical impedance by the speed of sound will yield ρ_1, the density of the gas in the tube. From ρ_1 the density of the ambient gas is

$$\rho = \frac{\rho_1 T_3}{T_1},$$

where T_3 denotes the temperature of the thermostatically controlled tube and T_1 the ambient gas temperature measured by the resistance thermometer. From the ambient gas density and temperature, the mean molecular mass is found by applying the gas law

$$\overline{M} = \frac{\rho RT}{p},$$

where p is measured by the pressure experiment. Since $\overline{M}/\overline{\gamma}$ has been given by the velocity measurement, $\overline{\gamma}$ can now be determined.

In Figure 2, a mixture of the three gases N_2, CO_2, and A is shown. It is generally accepted that these gases are probably the major constituents of the atmosphere of Venus. The $\overline{M}/\overline{\gamma}$ point of an arbitrary mixture of these gases must

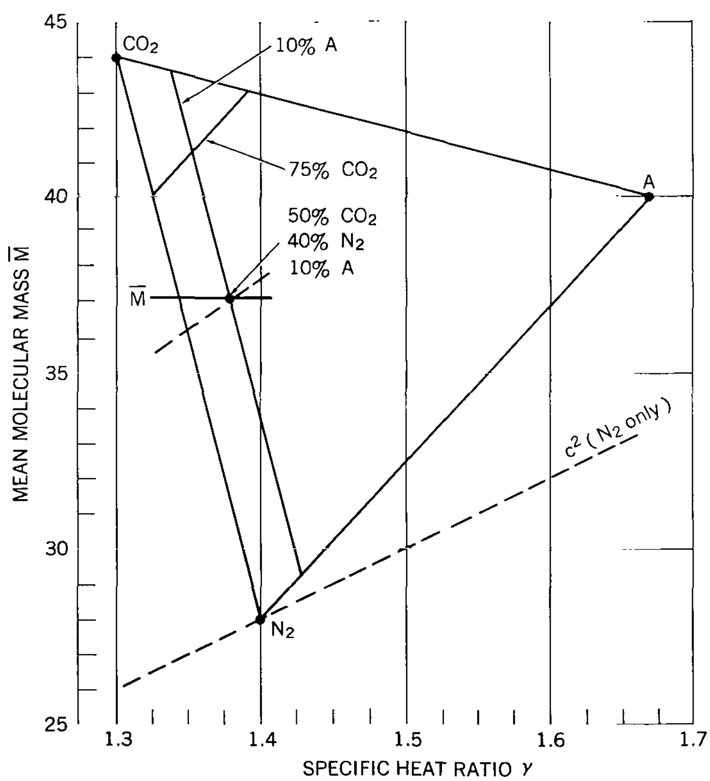

Figure 2—A particular mixture of nitrogen, carbon dioxide, and argon corresponding to a unique position on a diagram of mean molecular mass versus the specific heat ratio. The measurement of two independent parameters such as molecular mass (solid horizontal line) and velocity of sound (dashed diagonal line) determines the abundance of the three gases in the mixture.

fall within the triangle formed by the CO_2, N_2, and A points. According to present estimates, the possible amounts of water vapor, oxygen, and other gases are too small to contribute appreciably to $\bar{M}$. Curves of constant sound velocity c^2 are straight lines through the origin. The relative abundances of the respective components in the three-gas mixture are completely determined by the measurements of c and $\bar{M}$.

The CO_2 concentration found by the acoustical method is not as accurate as the one derived by optical means, which will be described below, but is a good independent check. Also, as mentioned above, agreement between the optical and the acoustical CO_2 determination is a conclusive test of the hypothesis that the atmosphere consists mainly of nitrogen, carbon dioxide, and argon.

The proposed technique (Figure 3) is to measure the velocity of sound through the gas in a spiral tube about 2 m in length and 1 cm in diameter. For ease in illustration Figure 3 shows a linear arrangement of this tube. At one end of the tube a generator drives a small sonic transducer at a constant frequency of about 4 kc. Two identical condenser microphones are placed along the tube with a nominal 4 wavelength separation. Both microphones resonate above 10 kc and form part of the wall of the tube. The test tube is extended beyond the second microphone and is acoustically terminated by damping material and rough wall surfaces to avoid reflections and standing waves in the tube. Since the two microphones and their amplifiers are identical, their phase shifts cancel each other. The phase shift as measured by the phase comparator is determined only by the wavelength of sound in the medium and, since the generator frequency is constant, by the velocity of sound in the gas.

In addition to the determination of the speed of sound, the instrument is capable of measuring the density of the gas in the tube. The mechanical and electrical impedance of the sound generator are chosen so that the velocity of the diaphragm is essentially independent of the acoustic radiation impedance of the tube. Under these conditions the sound pressure developed in the air contained in the tube is proportional to the acoustical impedance. Since the microphone used responds to sound pressure, the electrical signal generated by the microphone is proportional to the acoustic impedance of the gaseous medium. This constant of proportionality, which also contains the transducer sensitivity, can easily be determined by calibration in an N_2 atmosphere over a nominal pressure range.

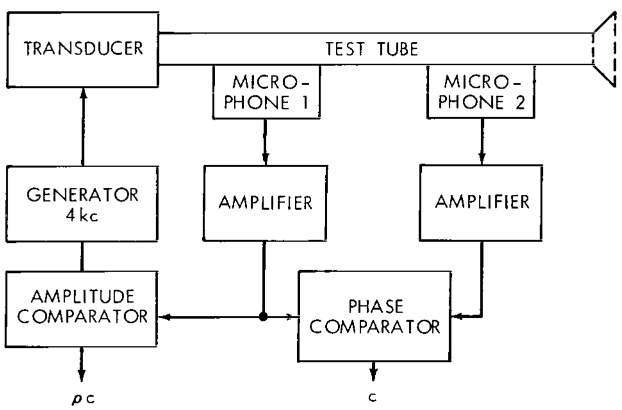

Figure 3—Block diagram of the acoustic experiment. The phase comparator gives the velocity of sound in the gas and the amplitude comparator yields the density and mean molecular mass using, in addition, temperature information derived by other sensors.

The accuracy requirements imposed on the speed of sound determination can be judged by considering the values shown in Table 1. A controlled gas temperature of 320 °K was assumed. The first and last rows represent what are presently considered to be the boundaries for the composition of the Cytherean atmosphere. The instrument is designed to cover the range from about 290 to 365 m/sec. The two microphones, 4 wavelengths apart, register phase differences between 0 and 360 degrees over the 75 m/sec change in velocity. A ±1 percent accuracy in the phase measurement yields the velocity of sound to ±0.75 m/sec, giving an overall accuracy of ±0.25 percent.

Table 1

Velocity of Sound for Various Possible Atmospheres of Venus

Gas	Velocity of Sound (m/sec)
100% N_2	364
95% N_2 + 5% A	362
95% N_2 + 5% CO_2	358
80% N_2 + 10% CO_2 + 10%A	349
10% N_2 + 80% CO_2 + 10%A	292

Calculation of the velocity of sound in Table 1 was based on the ideal gas law. It is more accurate to use Van der Waals' equation, and it can be shown that this may affect the fourth significant figure in the velocity term. Furthermore, the specific heat of gases shows a frequency dependence in the vicinity of molecular relaxation frequencies. This condition is especially true for CO_2 at low pressures and is one of the reasons why a relatively low operating frequency was chosen for the experiment. Because of these conditions, calibration of the instrument will be performed in an artificial atmosphere for a number of N_2:CO_2:A ratios.

Figure 4 shows a breadboard apparatus used to experimentally check the method of obtaining the mean molecular weight and density of unknown gas mixtures by acoustic means. Condenser microphone cartridges are used at the two smaller holes to measure phase and amplitude. The electronic

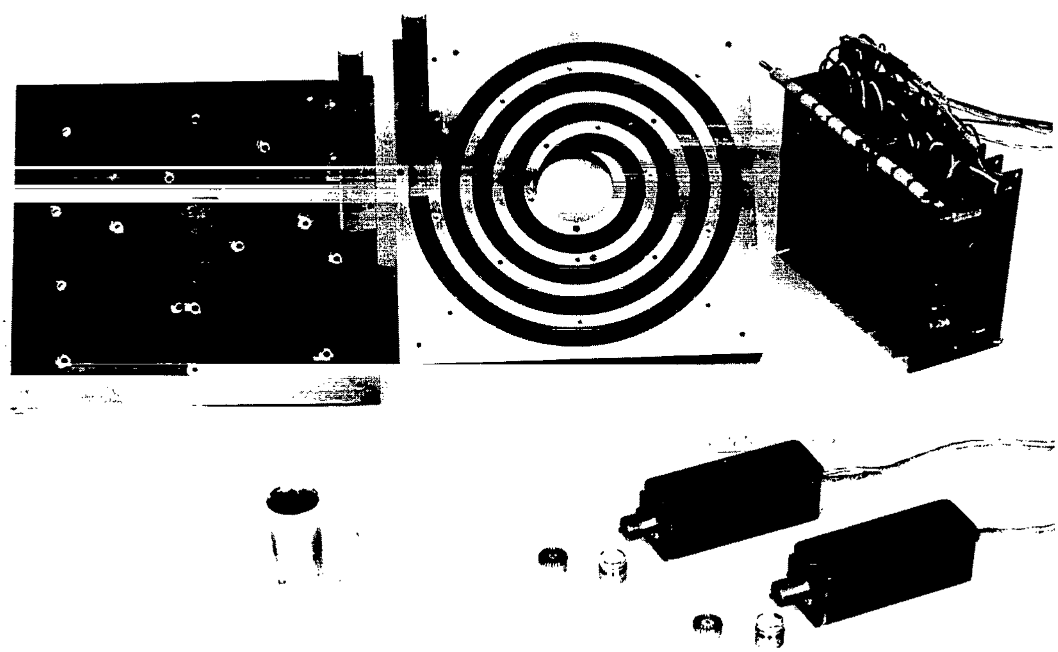

Figure 4—A breadboard model to verify the feasibility of the acoustic experiment. An aluminum block with a spiral sound path houses the driver in the center; condenser microphones are inserted into threaded holes which are visible in the spiral groves.

breadboard converts the acoustic phase angle between the microphones to an analog voltage. The velocity of sound in various media has been measured to an accuracy of ±0.1 percent with this instrument.

CO_2 CONCENTRATION

Measurement of this quantity is of critical importance for problems such as atmospheric heat balance and the efficient design of planetary entry capsules. A specific experiment, based on the absorption of radiation from an infrared source over a known path length in a strong absorption band, will accurately determine the CO_2 content. Measurements will be taken at constant time intervals during the descent phase. Calculations on the expected absorption have been made using the laboratory data of Howard, Burch, and Williams (Reference 40). For the pressure range of most interest ($0.01 < p < 10$ atm.) a separation of a few centimeters between the source and detector will be used. In Figures 5 and 6 the results are shown for the 2.7μ band with a 10 cm path length and for the 4.25μ band with a 1 cm path length.

From the instrumental point of view, the 2.7μ band is more desirable. Although some overlapping water vapor bands have to be considered, it can be shown that a high moisture content (which has never been detected in spectroscopic data of Venus from Earth) would cause only negligible absorption and would, therefore, not interfere with the determination of CO_2 in this band. Hence, a 0.2μ band centered at 2.7μ and one at 4.25μ are considered.

It can be seen from Figures 5 and 6 that for a particular pressure, 0.3 to 1 atm. for example, the transmittance depends very much on the relative CO_2 content, becoming more sensitive for smaller CO_2 concentrations. The instrument used is essentially self-calibrating, since the transmittance is almost unity at low pressures (very high in the atmosphere) and becomes practically zero after a descent of several pressure scale heights. This allows accurate measurement independent of moderate changes of detector sensitivity.

Solar radiation cannot be considered as a source of radiation for two reasons: First, a landing on the dark side of Venus is most likely for an early (minimum energy) trajectory, and also direct transmission to Earth will probably be necessary. Second, clouds would interfere with direct absorption methods. A light source on board was considered most suitable. A small linear filament can be made to survive the entry shock, but temperatures in the 800°-1000°K range are required after the deceleration phase. The filament will be heated by a pulsed current producing an alternating component in the infrared flux. This scheme completely avoids a mechanical chopper and, therefore, moving parts. The effective modulation of the source which can be achieved is very high even for a relatively small change in the black body temperature of the filament (Figure 7).

The detector will be a thermopile evaporated on a solid low-heat-capacity material. This detector is sensitive enough and lends itself well to a rugged construction capable of operating over a wide range of ambient temperatures.

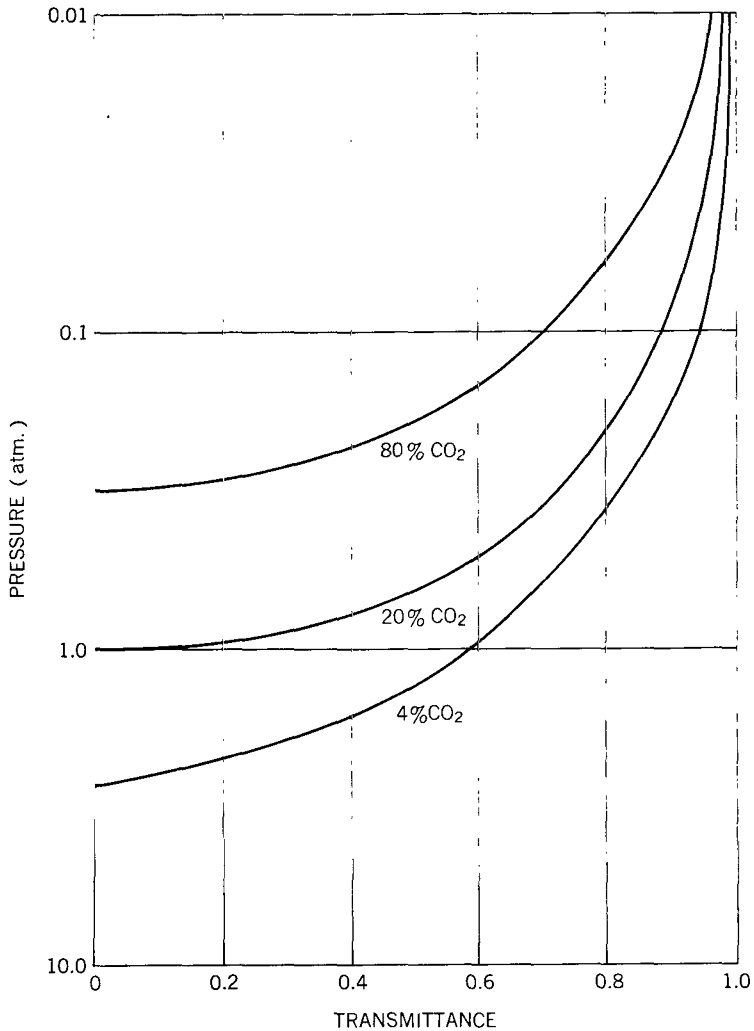

Figure 5—Transmittance versus ambient gas pressure for a 1 cm path length in the 4.25 μ CO_2 band. Calculations have been made for a 0.2 μ bandwidth and various CO_2 concentrations. The rapid increase in infrared absorption with an increase in pressure is due not only to the rise in the amount of gas in the fixed path length but also to an increase in the absorption coefficient (pressure broadening effect).

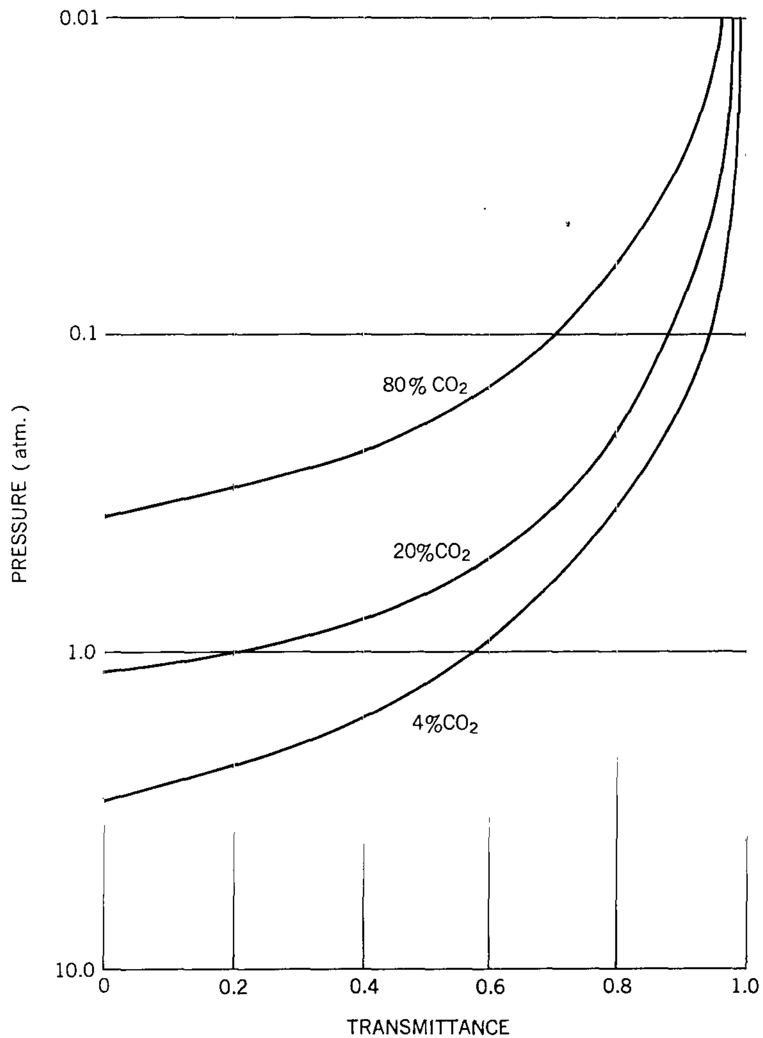

Figure 6—Transmittance versus pressure for a 0.2 μ bandwidth at the 2.7 μ CO_2 absorption band and with a 10 cm path length.

H_2O CONTENT

Water vapor as well as CO_2 could act as an important constituent to generate a greenhouse effect. Water vapor has never been conclusively detected by spectroscopic or radar techniques from Earth; it is desirable to confirm whether or not it is in the Venus atmosphere by *in situ* experiments. However, a spectroscopic detection method on a capsule similar to the one described for CO_2, even one using the same infrared source, is not very practical. The strongest water vapor absorption band, centered at 6.3 μ, is much weaker than the 4.2 μ CO_2 band and, although water droplets or ice clouds would require a saturated atmosphere in their vicinity, the water vapor concentration—even at 100 percent relative humidity—is rather small. Therefore, practical absorption path lengths are in the meter, rather than centimeter, range.

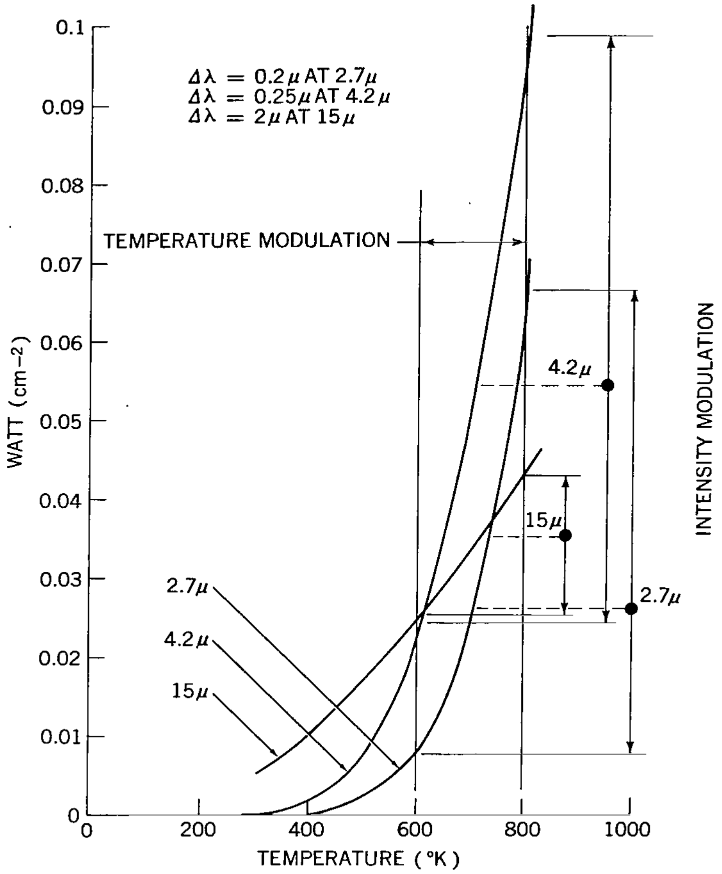

Figure 7—Comparison of available energy and modulation efficiency of the source as a function of equivalent black body temperature. For a 700°K black body, the 4.2 μ region yields the strongest signal and the 2.7 μ region the highest intensity modulation. Temperature modulation of ±100°K is assumed.

For early missions, humidity sensitive elements based on the change of resistance in a tungsten oxide element are more practical than any other. Such elements are commercially available. The sensor is cleaned by heating it to cherry red, and sterilization by heat is therefore easy. Very low values of relative humidity are more difficult to measure since the resistance elements now available reach impedances on the order of $10^9\Omega$, compared with the 0.5 $M\Omega$ needed for 100 percent relative humidity.

CLOUD DETECTION BY SCATTERING

Scattering experiments can determine the particle size, density, and even the refractive index and therefore the composition of particles in a cloud. But, even without phase angle and polarization studies, very useful information can be gained by simple techniques since the ability to detect the presence or absence of clouds, as the capsule descends in the atmosphere, can yield important conclusions. For instance, a low relative humidity, detected by the tungsten oxide detector described above, and the presence of clouds clearly would rule out water or ice clouds. The pressure, temperature, and concentration measured by the capsule can be used to plot a curve on the phase diagram o of a possible cloud substance (Figure 8). Substances which are the candidates for cloud particles include formaldehyde, dust, salt, ammonium nitrate, polymers of carbon suboxide, certain organic compounds (malonic or oxalic acid), nitrogen peroxides, and water. Some of these have a low probability on the basis of present knowledge and more will be eliminated by the study of phase diagrams and pressure, temperature, and cloud occurrence data which will be obtained from Venus probes.

The simple experiment proposed here will detect clouds and give an estimate on their particle density. Again, since the scattering experiment must work on the planet's dark side, it must have its own light source. Two arrangements have been considered, both of which depend on the backscattering of light from cloud particles. The first one consists simply of a modulated light source and a detector without lenses, shielded from each other. The second method employs lenses to separate the cloud-detection area from the capsule (Figure 9). The first has the advantages of simplicity and higher sensitivity whereas the second has the advantage of separating the detection area from the vicinity of the capsule. The detector can be simply a diffused-junction silicon diode (solar cell) operated in the photovoltaic mode. The light source can be designed for a power consumption below 3 watts and still yield a sufficient signal-to-noise ratio of 100 to 1.

The spectral response of silicon cells peaks at about 8500A. These cells can be made very rugged and should easily withstand

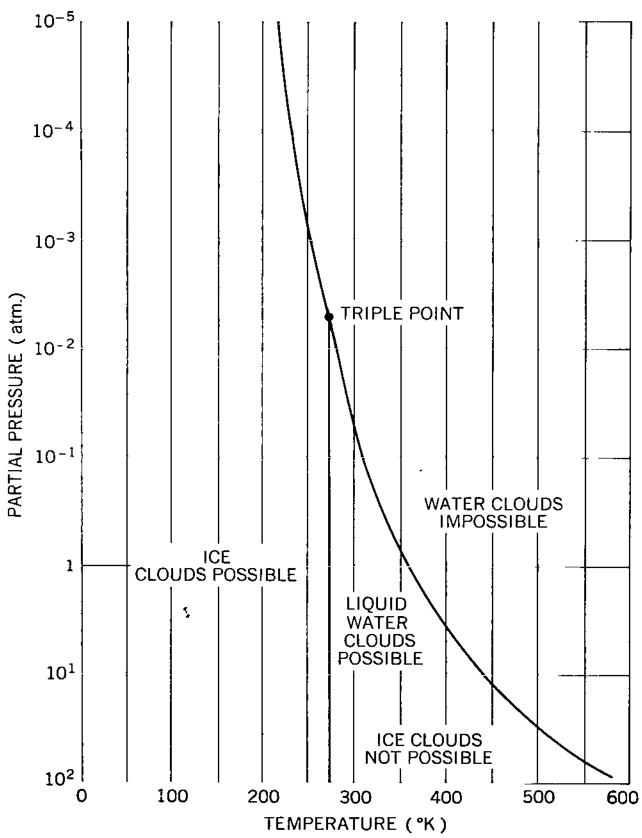

Figure 8—Phase diagram of water. By using this and partial pressure, and temperature data derived from the sensors, it may be possible to rule out the existence of liquid water or ice clouds. Similar diagrams for other constituents are also available.

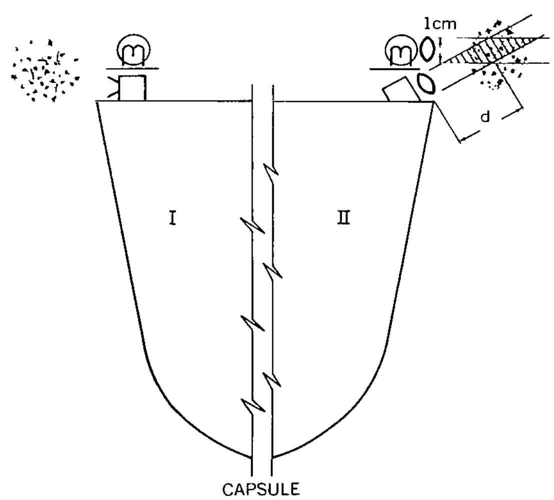

Figure 9—Schematic view of two cloud detectors. Each consists of a modulated light source and a receiver. Version I operates within a large solid angle, and version II uses optical elements to separate the sensitive detection area from the immediate vicinity of the capsule.

sterilization temperatures. The source may be a simple tungsten lamp or a pulsed arc of the xenon type—the spectral characteristic of the silicon type is especially favorable for a tungsten source.

CONCLUSIONS

A summary of the experiments and their weight and power consumption, excluding structure and information-handling electronics (analog-to-digital converter, storage memory, transmitter, etc.), is given in Table 2.

Table 2

Proposed Experiments.

Parameter	Value or Method
Pressure (aneroid potentiometer)	0-0.7, 0-7, and 0-70 atm. or logarithmic response
Temperature (platinum resistance thermometer)	150°-750°K; 180°-330°K
Acoustic experiment	100 mb-10 atm., 290-365 m/sec
CO_2 experiment	Tungsten source; 4.2 μ
H_2O experiment	Platinum oxide detector
Scattering experiment	Source on board, visible light
Total weight of experiments	12 lb
Total power consumption	15 watts

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